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APPLICATION OF GROUND PENETRATING RADAR TO AID RESTORATION PLANNING FOR A DRAINED CAROLINA BAY

Ryan P. Szuch[1,3], Jeffrey G. White[1], Michael J. Vepraskas[1], and James A. Doolittle[2]
[1]*Department of Soil Science*
Box 7619
North Carolina State University
Raleigh, North Carolina, USA 27695
E-mail: jeff_white@ncsu.edu

[2]*USDA-NRCS*
c/o USDA Forest Service
11 Campus Blvd., Suite 200
Newton Square, Pennsylvania, USA 19073

[3]*Current address: Blasland, Bouck, & Lee, Inc.*
8 South River Road
Cranbury, New Jersey, USA 08512

Abstract: Clayey subsurface strata in precipitation-driven wetlands act as aquitards that retain water and can affect wetland hydrology. If the aquitard layers have been cut through by drainage ditches, then restoring wetland hydrology to such sites may be more difficult because of the need to fill ditches completely with low hydraulic conductivity material. Ground penetrating radar (GPR) surveys were conducted to determine the depth and continuity of shallow clay layers and identify those that have been pierced by drainage ditches at Juniper Bay, a 300-ha drained Carolina bay in North Carolina, USA that will be restored. Carolina bays are a wetland type that occur as numerous, shallow, oval-shaped depressions along the Atlantic Coastal Plain. The GPR interpretations found that moderately fine-textured (clay loam, sandy clay loam, silty clay loam) and fine-textured (sandy clay, silty clay, clay) aquitards underlay coarser-textured horizons in most of the bay at an average depth of 1.6 m. Extensive ground truthing showed that, on average, GPR predicted the depth to these aquitards to within 16% of their actual depth. An atypical GPR reflection in the southeast sector of the bay was interpreted as a fluvial deposit without aquitards until a depth of 3 to 5 m. This area may require different restoration strategies than the rest of the bay. By comparing the depths of aquitards and drainage ditches, several areas were identified as likely locations of ditch-induced aquitard discontinuity that may require filling or lining of suspect ditches to prevent potential water losses if there are downward hydraulic gradients. Cost estimates by two professional firms indicated that GPR could provide large volumes of data with cost and time efficiency. GPR surveys are proposed as a useful tool for characterizing potential wetland restoration sites on the Atlantic Coastal Plain and other regions with similar soils.

Key Words: wetland hydrology, aquitards, lacustrine deposits, fluvial deposits

INTRODUCTION

Carolina bays are a wetland type found along the Atlantic Coastal Plain that occur as shallow, oval-shaped depressions oriented in a northwest to southeast direction. An estimated 500,000 bays exist from New Jersey to northern Florida, USA (Melton and Schriever 1933, Frey 1950, Prouty 1952, Bliley and Pettry 1979), with about 80% of them occurring within North and South Carolina (Prouty 1952). Bays range in size from one to thousands of hectares and have unique vegetative characteristics and ecological value (Sharitz 2003).

Many Carolina bays have been drained and converted to agriculture because they are relatively flat and contain potentially productive but seasonally saturated organic and mineral soils (Sharitz and Gresham 1998). In a study of bays of South Carolina, Bennett and Nelson (1991) found that 97% of bays have been disturbed, mainly by logging (34%) and/or agriculture (71%). Plugging of the drainage systems of converted bays would likely restore wetland hydrology. For this reason, the numerous drained Carolina bays present excellent opportunities for wetland mitigation.

Although soils of Carolina bays can be quite variable (Frey 1950, Saunders 1990, Reese and Moorehead 1996), many contain continuous or nearly continuous subsurface clayey horizons (Sharitz and Gibbons 1982). These clayey layers may act as aquitards to perch water tables and/or restrict ground-water losses during certain times of the year. Johnson (1942) and Lide et al. (1995) suggested that bay hydraulic gradients are controlled by subsurface flow over fine-textured soil horizons. A ground penetrating radar (GPR) survey of several bays in South Carolina, including one studied by Lide et al. (1995), identified clayey interior bay sediments that were suspected to have a strong influence on bay hydrology (Grant et al. 1998).

GPR has been used in various settings to map the depths to clayey soil horizons and stratigraphic layers (Collins and Doolittle 1987, Hubbard et al. 1990, Dominic et al. 1995, Kettles and Robinson 1997, Doolittle et al. 2000, Van Dam and Schlager 2000, Nobes et al. 2001). In environments other than wetlands, GPR surveys have delineated clayey soil horizons that were shown to impact local hydrology greatly (Asmussen et al. 1986, Tomer et al. 1996). Soil horizons with aquitard properties that are important to sustaining wetland hydrology have been mapped by GPR as well (Lapen et al. 1996, van Overmeeren 1998). Lapen et al. (1996) mapped the continuity of a placic horizon (strongly cemented, iron-rich, mineral horizon) along a wetland catena in Newfoundland. The GPR survey revealed that the placic horizon was present beneath wetland bogs but absent beneath upland heath communities. The authors found that the placic horizon was restricting ground-water flow and was thus hydrologically and ecologically important in sustaining the bogs. Similarly, van Overmeeren (1998) found that GPR was useful for mapping cemented layers that acted to hold water in fens of the Netherlands.

Hydrologic models can be used to evaluate the effects of ditch plugging and surface treatments on restored hydrology (Skaggs 1999). To calibrate such models, knowledge of the depth of the 'restrictive layer' is usually needed. GPR may be an efficient and effective means of gathering such information in order to model the current hydrology of the bay and help determine how wetland hydrology could be restored most efficiently.

The goal of this study was to test the usefulness of GPR for characterizing the aquitards of a drained Carolina bay (Juniper Bay) in North Carolina (Figure 1). Specific objectives were 1) to determine the depth, lateral extent, and continuity of clayey aquitards throughout Juniper Bay and 2) to determine where drainage ditches may have pierced aquitards, potentially allowing water to drain and exit the site. For informational purposes, a qualitative comparison of proposed surveys using GPR and conventional methods (i.e., coring) was conducted to determine if GPR could provide a cost- and effort-efficient alternative for screening restoration sites and supplementing restoration plans.

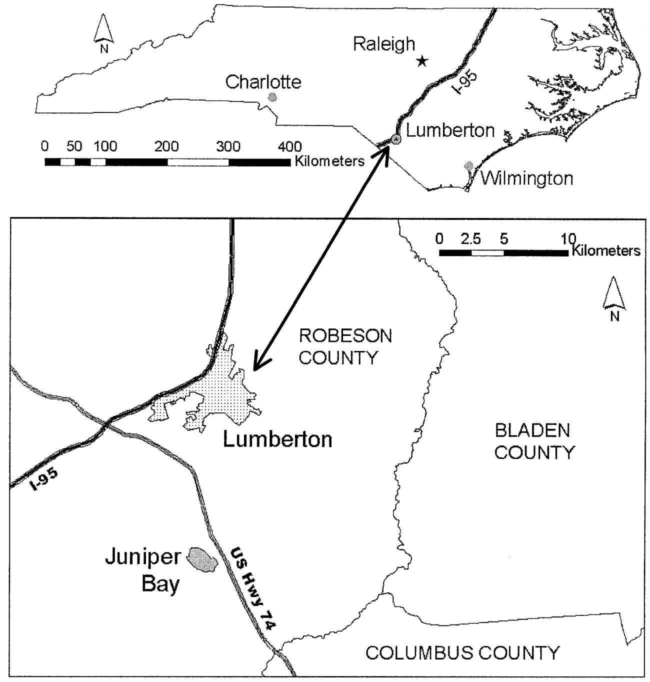

Figure 1. Map of North Carolina and the Lumberton area showing location of the Juniper Bay study site. Arrow indicates the location of Lumberton on both large- and small-scale maps.

MATERIALS AND METHODS

Study Area

The study site was Juniper Bay, a 300-ha drained Carolina bay located approximately 16 km southeast of Lumberton, North Carolina at 34°30′30″N 79°01′30″W. (Figure 1). The bay was drained for agriculture by an extensive network of surface ditches that were installed beginning in 1971 and completed in 1986. In 2000, the North Carolina Department of Transportation (NCDOT) purchased the property. NCDOT intends to restore wetland hydrology and vegetation that meet the requirements of the U.S. Army Corps of Engineers for as large an area as possible in order to receive wetland mitigation credit. Restoration efforts were initiated in June 2003. Principal soils mapped within Juniper Bay are Leon fine sand, Pantego fine sandy loam, Ponzer muck, and Rutlege loamy sand (McCachren 1978); see Table 1 for the taxonomic classification of these soils.

Ground water appears to enter Juniper Bay from the northwest and southeast boundaries (Figure 2), which are higher in elevation, and exit through the northeast and southwest boundaries, which are lower in eleva-

Table 1. Classification of soils mapped at Juniper Bay.

Soil Series	Family Taxonomy
Leon	Sandy, siliceous, thermic Aeric Alaquods
Rutlege	Sandy, siliceous, thermic Typic Humaquepts
Pantego	Fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults
Ponzer	Loamy, mixed, dysic, thermic Terric Haplosaprists

McCachren (1978).

tion (Luginbuhl 2003). The ditch drainage system carries water primarily to a main collector ditch oriented approximately northeast to southwest that divides the western third of the bay from the eastern two thirds (Figure 2). Water in this main ditch and in the perimeter ditch exits the bay to the southwest. The hydraulic gradients at the site are not fully understood, but research to date indicates that in the shallow ground water at some times of the year, it is controlled in large part by the deep perimeter ditch, towards which water moves from both inside and outside the bay. Within the bay, the hydraulic gradient is probably generally downward, but there may be areas within the bay where the gradient is upward.

The area of Juniper Bay is subdivided into ''fieldlets,'' defined as areas of the bay confined by ditches on all sides (Figure 2). In 2000, an initial investigation of the bay's stratigraphy was performed via coring with a truck-mounted hydraulic drilling machine with an overshot wireline split-barrel sampler for continuous coring with a hollow stem auger. The core segments were ~1.5 m long and ~8 cm in diameter. Within the rim of Juniper Bay and in the adjacent area, 29 cores were obtained, 22 to a depth of ~6.1 m and 7 to a depth of ~15.2 m. The coring sites within the bay were selected by placing an equilateral triangle grid over a soil map of the bay (McCachren 1978), and choosing a number of core locations that would yield information representative of each soil type and be economically feasible. Once extracted, the cores were examined to describe the depth, thickness, texture, and color of the soil or sediment layers. Evaluation of these cores revealed that the bay is underlain by complex, interbedded layers of sandy and clayey material (Ewing et al. 2001).

GPR Survey

The GPR surveys of Juniper Bay were performed in December 2000 and June 2001 to provide additional information on the subsurface. At the time of the first GPR survey, the bay was planted in cotton (*Gossypium hirsutum* L.); for the subsequent survey it was fallow. The surveys included transects totaling over 23 km. Survey transects were established in 15 fieldlets where

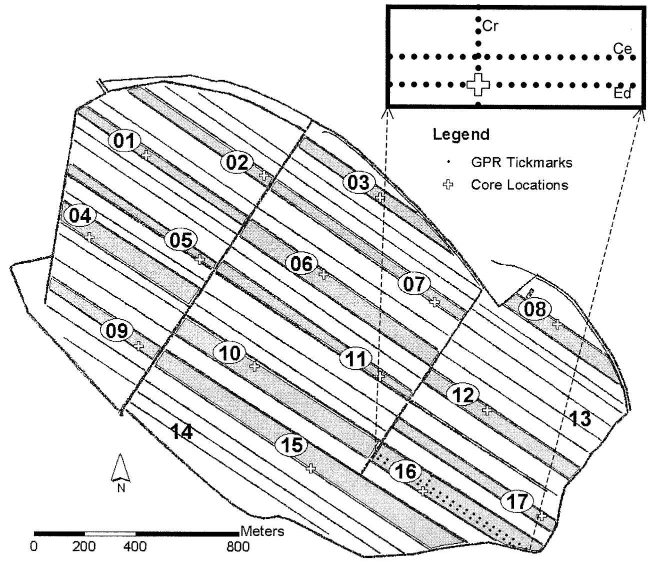

Figure 2. Map of Juniper Bay showing drainage ditches, fieldlets, and original core locations. GPR surveys were conducted in gray-highlighted, numbered fieldlets. (N.B.: Fieldlet 13 was always too wet to survey, and GPR data from Fieldlet 14 were lost.). In Fieldlet 16 and blowup diagram, an example of the orientation of the center (Ce), edge (Ed), and cross (Cr) GPR transects is shown along with the core location. Each dot represents a tick mark located every 30 m along the GPR transect.

cores had been obtained previously (Figure 2). Note that while Figure 2 shows fieldlets ranging from 1 to 17, Fieldlet 13 was always too wet to survey, and GPR data from Fieldlet 14 were lost due to an equipment malfunction. Within each fieldlet, three GPR transect surveys were performed: ''center''—longitudinal transect down the center of the fieldlet; ''edge''—longitudinal transect along the ditch edge of the fieldlet; and ''cross''—lateral transect across the fieldlet, intersecting the core location (Figure 2). Prior to the survey, flags were placed every 30 m along the transects, and their locations were marked on the GPR trace by the operator as each flag was passed (Figure 3). A differential global-positioning system (DGPS) was used to georeference each flag.

The GPR unit used was the Subsurface Interface Radar System-2000 (Geophysical Survey Systems, Inc.[GSSI]). A 120 MHz (2.5-m wavelength) antenna was used, with scanning time of 200 nanoseconds (ns). The GPR was calibrated in the field using a lift test to define the soil surface. RADAN NT (version 2.0) software was used to process the radar profiles. Processing included color transformations, marker editing, distance normalization, and range gain adjustments. All radar profiles were converted into bitmap images using the GSSI Radan to Bitmap Conversion Utility (version 1.4) using the red (+)—blue (−) color table.

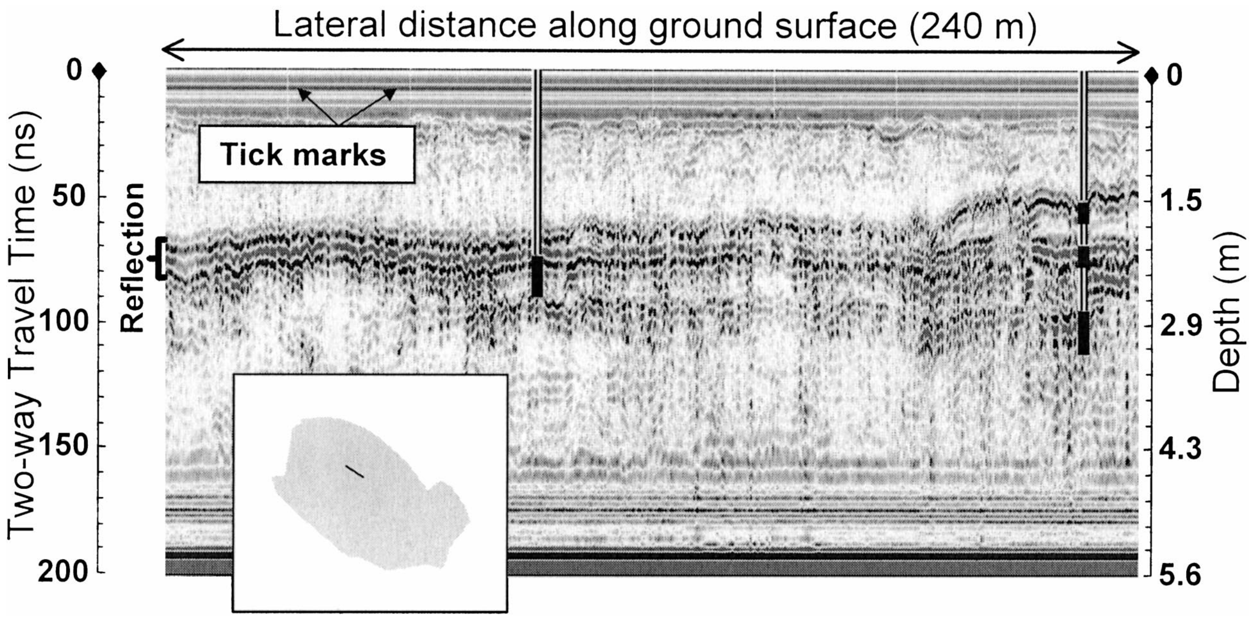

Figure 3. Example of a GPR profile from survey at Juniper Bay (see inset for location). Tick marks were placed by GPR operator in the field and correspond to the location of survey flags every 30 m. Vertical axis originally depicts two-way travel time (left side) and after calibration depicts approximate depth (right side). Multiple dark lines along the profile indicate a GPR reflection and are interpreted to represent an aquitard. A single reflection can be seen on the left side of the profile, and the reflection diverges into multiple, overlying reflections toward the right side. The reflection pattern was confirmed by coring. Vertical bars along the profile represent core locations (width of cores not to scale). Black areas of these bars indicate clayey texture, and vertically striped areas of bars indicate sandy texture.

Bitmaps were imported into Microsoft Office PowerPoint 2000 as JPEGs. PowerPoint drawing tools were used to draw a line along interface reflections apparent in the bitmap as the first positive (red) or negative (blue) pulse of greater intensity than those above. For consistency, a single individual made all of these interpretations. A two-way travel time scalebar was added to span the GPR scan, with demarcations based on the 200-ns scanning time. The scalebar was moved along the scan, and the two-way travel times of the reflection lines were recorded at locations corresponding to 15-m horizontal intervals along the scan (i.e., halfway between and at every tick mark). Two-way travel times for the reflections were corrected (~7–8 ns) based on the lift test identification of the surface, resulting in a two-way GPR travel time from the surface to the purported interface.

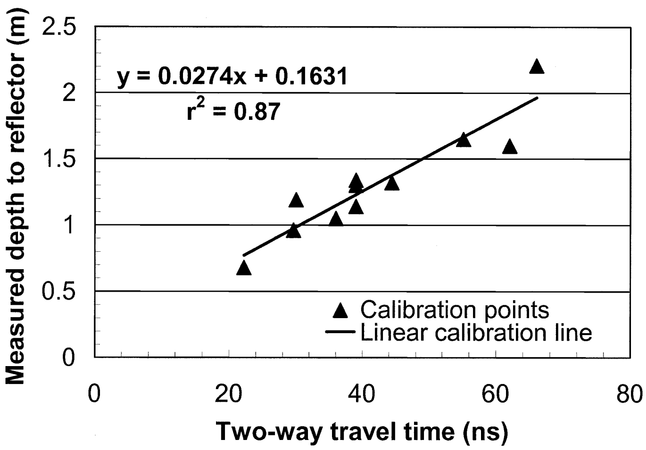

Figure 4. GPR calibration equation developed based on reflector-interface matching at 11 locations throughout Juniper Bay (Szuch et al. 2004). The calibration equation related field-measured depth to an interface (m) to two-way GPR travel time (ns). Minimum, maximum, and average estimated GPR wave velocities were 0.051, 0.079, and 0.063 m ns^{-1}, respectively.

From the bitmap images, a linear calibration equation was developed (Figure 4; Szuch et al. 2004) based on reflector-interface matching at 11 locations throughout the bay using bucket auger cores taken during the GPR surveys. The calibration equation related field-measured depth to an interface to two-way GPR travel time as

$$\text{Depth to interface (m)} = 0.0274 \times (\text{two-way travel time; ns}) + 0.1631. \quad (1)$$

Minimum, maximum, and average estimated GPR wave velocities for the calibration points were 0.051, 0.079, and 0.063 m ns^{-1}, respectively. From the bitmap

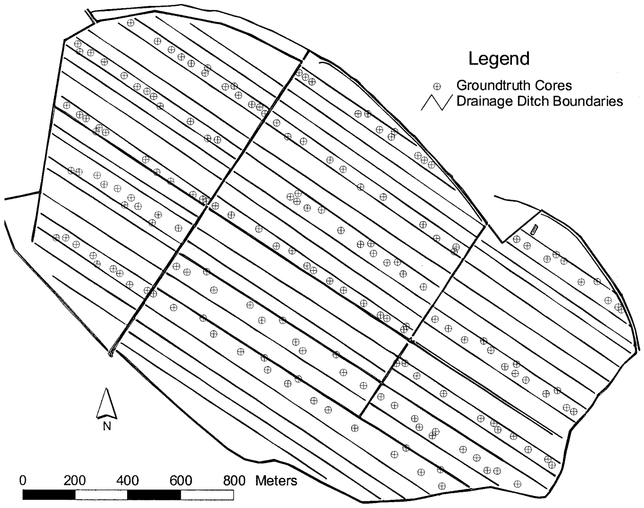

Figure 5. Map of Juniper Bay showing locations of ground-truth cores extracted to verify GPR-derived depths to interfaces where clay content increased.

images of the transects (e.g., Figure 3), depths to reflections that were expected to be clayey soil horizons were predicted when possible (n=1450) at 15-m intervals along all transects using the calibration equation [1].

Based on these predictions, the depth to the shallowest clayey horizon was interpolated via kriging over the entire area of Juniper Bay. Geostatistical software, GS+ (Gamma Design), was used to model the semivariogram for the interpolation data. This model was used to set the kriging parameters in ArcGIS—Geostatistical Analyst (ESRI).

Ground-Truthing Survey

To verify the predicted depths to the interfaces where clay content increased, additional coring was done at 123 observation points selected randomly along the center traces and at 43 points selected randomly along the edge traces (Figure 5); 14 of the original cores were also used. A DGPS was used to navigate to the observation points. Coring was mainly by bucket auger, but six deep cores in Fieldlet 8 were taken using a Giddings hydraulic probe. The occurrence and depth of clay-rich horizons were recorded in the field. Some of these horizons were identifiable by visually distinct boundaries; whether apparent visually or not, occurrence of relatively finer-textured horizons was determined primarily by field analysis of ''texture by feel.'' Samples were collected from these and overlying layers to determine percentages of sand, silt, and clay (particle size distribution). Samples were air-dried and ground to pass a 2-mm mesh sieve. Particle size analysis was determined by the hydrometer method (Gee and Bauder 1986). When necessary, organic matter was removed by oxidation with 30% H_2O_2 and heat. Sand fractions in selected samples were determined by sieving.

Accuracy of the GPR surveys was calculated as the absolute deviation between predicted and observed depths to moderately fine-textured (clay loam, sandy clay loam, silty clay loam) and fine-textured (sandy clay, silty clay, clay) horizons:

$$\text{Absolute Deviation} = |\text{P.D.} - \text{O.D.}| \qquad (2)$$

where P.D. was the predicted depth based on GPR interpretation, and O.D. was the observed depth based on coring.

Determining Depth of Ditches

The main source of data for determining the depth of drainage ditches was a detailed topographic map created by aerial photogrammetry using ground control points. This was developed by the NCDOT and imported from MicroStation CAD (Bentley Systems, Inc.) into ArcGIS geographic information system (GIS). The accuracy of the GIS map was tested by comparison with ditch depths measured manually in the field at 38 locations (not shown) throughout the bay.

Comparison of Cost and Time Requirements of GPR and Conventional Methods

For the qualitative comparison of GPR and conventional methods, a request for proposal (RFP) was created and submitted to two consulting firms (that shall remain anonymous). One firm would address the RFP via a GPR survey, and the other would employ a coring survey. The RFP asked that the depth of clayey aquitards be determined along the entire 43.6-km length of ditches at Juniper Bay. The proposals included the time and cost of fieldwork, associated analysis or interpretation, and report preparation. The GPR proposal included six cores that would be necessary for calibration and ground truthing. Three variations of the coring survey were considered, involving spacings of 15, 60, and 300 m between coring sites along the ditches.

RESULTS AND DISCUSSION

A characteristic example of a GPR profile from the survey of Juniper Bay is shown in Figure 3. From left to right, this GPS scan shows a single reflection at ~2 m depth that diverges into multiple overlying reflections. These reflections were initially interpreted as interfaces within the profile representing transitions from

Table 2. Summary statistics for percent sand, silt, and clay of layers above and within aquitards detected with GPR and for percentage point differences in sand, silt, and clay percent between these layers. The average soil texture above the aquitard was loamy sand, and within the aquitard, sandy clay loam. For the differences: positive values indicate increases from above to below, negative values indicate decreases from above to below; sand and clay minima and maxima represent both the magnitudes and the extremes of the differences; for silt, values listed are the extremes of the range of differences; smallest magnitude difference for silt was 0.3%.

Soil Layer	Statistic	Sand (%)	Silt (%)	Clay (%)
Above Aquitard	Average	85	6	10
	Minimum	63	0	3
	Maximum	95	25	18
In Aquitard	Average	59	15	26
	Minimum	20	0	8
	Maximum	89	38	56
Difference: above—within (percentage points)	Average	−25	9	16
	Minimum	−3	−23	3
	Maximum	−69	29	44

relatively coarse-textured soil horizons to ones with greater clay content relative to the overlying material (i.e., potential aquitards). Over the entire extent of the survey, the GPR detected such interfaces or boundaries between soil or sediment layers within approximately 5 m of the soil surface (not shown).

Core data confirmed that the interfaces detected by GPR occurred primarily between layers of different clay percentage. In the cores, these transitions had boundaries that were predominantly gradual, but in some instances appeared quite sharp, both in terms of their visual appearance, field textural analysis by feel, and laboratory particle size analysis. At some of the coring locations, multiple fine- and moderately-fine textured horizons were encountered. At five locations, no such horizons were found. At two of these, it was impossible to obtain sample at some depths due to sloughing of saturated slurry in the bore hole. In one case (detailed below), there was an atypical GPR profile in an area without shallow aquitards. In the other two cases, there may have been localized aquitard discontinuities that were too small to be detected by GPR.

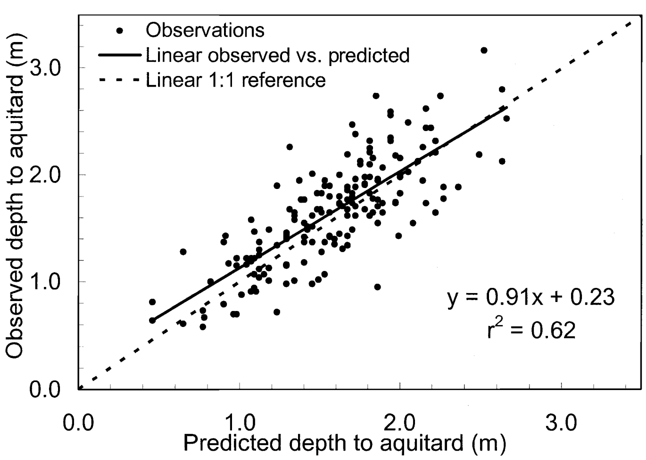

Figure 6. Plot (n=179) of observed depths to aquitards from coring versus predicted depths to aquitards based on GPR scans from surveys of Juniper Bay and the calibration equation in Figure 4 at the ground-truth observation points mapped in Figure 5.

Summary statistics for the textures of the soil materials above and below the interfaces detected are shown in Table 2. The layers above the interfaces had an average clay content of 10%, while those below averaged 26% clay. The average difference in sand content above and below the interfaces was even more pronounced, averaging 85% sand above and 59% below. Table 2 also shows summary statistics for the differences in sand, silt, and clay percentages between layers above and below the interfaces detected by GPR. The minimum difference in clay percentage in these layers was 3%, which was accompanied by similarly small differences in sand and silt content (not shown). This indicates that GPR sometimes detected interfaces with relatively small changes in texture; in such cases, differences in other factors such as moisture content, soil density, or mineralogy may have contributed to radar reflectivity. The textural class of horizons detected by the GPR ranged from sandy loam to clay. The sandy loam horizons were detected by the GPR when they were overlaid by sand or loamy sand horizons.

Accuracy

Depths to the interfaces where clay percentage increased were estimated from the GPR traces and compared to actual depths determined at the ground-truthing core locations (Figure 6) where such interfaces were found. The GPR depth estimates (n=179) were within 16% of the actual depth on average (Table 3). The average absolute deviation between predicted and observed depth to moderately fine- and fine-textured interfaces was 25 cm (SD = 19 cm). This deviation is

Table 3. Summary of accuracy in predicting depth to a subsurface interface for various GPR studies. Average error is the absolute deviation between observed and predicted divided by the observed depth, on a percent basis. Results are ranked by average error. Current study is shown in bold; the row labeled ''entire'' represents all ground truthing at Juniper Bay; the row labeled ''transect'' represents results only within a single fieldlet (12).

Source	Surveyed Distance (km)	Substrate	Interface Detected	Number of Observation Points	Observed vs. Predicted	Average Error (%)
Collins et al. 1989	0.09	loamy soil	bedrock	61	r = 0.98	4.1†
Birkhead et al. 1996	0.09	sand-gravel bar	bedrock	15	$R^2 = 0.85$	4.4#
Collins and Doolittle 1987	0.2	sandy spodosol	argillic horizon	4	na	5.2†
Asmussen et al. 1986	unknown (2.33 ha)	sandy soil	argillic horizon	8	r = 0.99	7.0‡
Birkhead et al. 1996	0.375	sand-gravel bar	water table	70	$R^2 = 0.97$	7.9#
Collins and Doolittle 1987	0.2	sandy spodosol	spodic horizon	4	na	9.1†
Doolittle et al. 2000	0.03	Alfisol	fragipan	21	r = 0.49	9.4‡
Szuch 2004—transect	0.63	sandy soil	clayey horizon	9	$r^2 = 0.80$	9.6‡
Lapen et al. 1996	0.5	Bog	various	10	r = 0.99	10.1‡
Vogt et al. 1996	13.8	flood deposits	Sediment over soil	25	$r^2 = 0.95$	10.1†
Szuch 2004—entire	23.2	various soils	clayey horizon	179	$r^2 = 0.62$	16.0‡
Asmussen et al. 1986—transect	1.6	sandy soil	argillic horizon	14	r = 0.95	57.1‡

† Calculated based on average or range of deviation and depth included in source.
‡ Calculated based on results at individual observation points included in source. This calculation produces a more accurate, and typically higher, percent error than if based on average deviation and depth.
# Reported as percent error in source.

somewhat greater than, but comparable to, other GPR studies that have predicted depth to a specific horizon or layer, as shown in Table 3. The GPR survey at Juniper Bay covered a much larger area than most of the studies in Table 3; therefore, spatial variation in soil properties that would impact GPR interpretation was probably greater as well. This spatial variation was likely the main cause of the elevated percent error at Juniper Bay. Further discussion of GPR use and accuracy for this study can be found in Szuch et al. (2004).

Mapping Aquitards with GPR

Interfaces at the tops of moderately fine- and fine-textured soil horizons or sediments were successfully mapped throughout Juniper Bay using GPR. These horizons should have lower saturated hydraulic conductivities than the overlying sandier horizons, and water tables should develop on top of them. As a result, the moderately fine- and fine-textured horizons mapped in this study will be called aquitards. The aquitards were found over most of the survey transects, and in many instances, there were two to several clay-rich horizons overlying each other (Figure 3). Depths to aquitards ranged from ~0.5 to 5.3 m, with an average depth of ~1.6 m. The interpolated variation in depth to the shallowest aquitard across Juniper Bay is shown in Figure 7. The largest extent of shallow aquitards (less than 1-m deep) is in the northeast section of the bay (Figure 2: area surrounding core/fieldlet 8). Field observations have consistently shown that this region of the bay remains saturated near the surface throughout the year; thus, the aquitards may play a significant role in maintaining wet conditions.

Based on our field coring, no aquitard was detected within 5 m of the surface over a small portion of Juniper Bay in the southeast sector (Figure 7). In addition, the pattern of the GPR traces found in this area differed from the other areas of Juniper Bay (Figure 8). A guide to identifying the types of sediments seen in GPR traces in the Netherlands was presented by van Overmeeren (1998). The interpretations in that report suggest that most of the soil or sediment layers detected in Juniper Bay appear to be lacustrine in that their GPR facies consist of relatively flat, subparallel, nearly continuous reflections over moderate distances (hundreds of meters). Such layering is consistent with current theory that suggests that the bays were formerly shallow lakes or ponds (Grant et al. 1998). However, the atypical GPR signature in the southeast sector appears fluvial in nature because the reflections are neither flat nor continuous, but chaotic, wavy, and discontinuous (van Overmeeren 1998, Vandenberghe

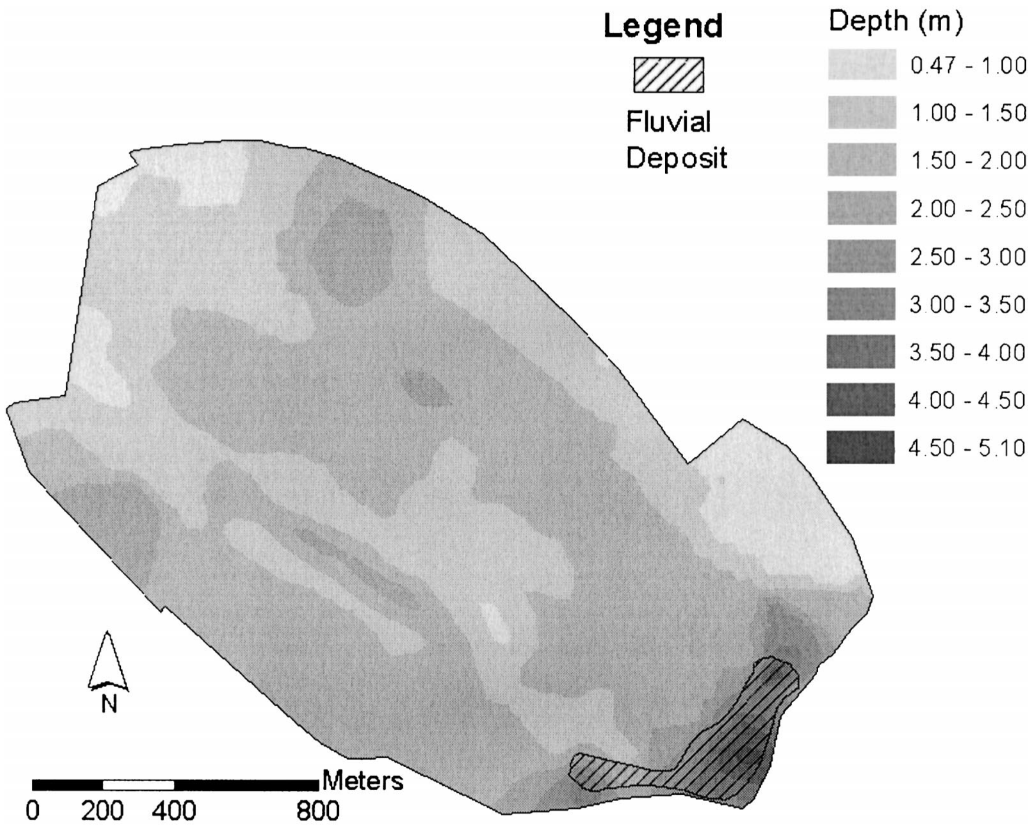

Figure 7. Interpolated map of depth to shallowest aquitard within Juniper Bay, based on GPR interpretation. Semivariogram used for interpolation via kriging had a range of 1000 m, sill of 0.41 m^2, and nugget of 0.08 m^2. Map also displays the location and extent of the atypical GPR facies (left scan in Figure 8) in the southeast sector of the bay that appears to be a fluvial deposit without shallow aquitards. If there are downward hydraulic gradients in this area, restoration of wetland hydrology may be hindered.

and van Overmeeren 1999). Coring by hydraulic drill rig at six locations within this area encountered no moderately fine- nor fine-textured horizon until 5.8 m. The coring and GPR data suggest that the depositional environment in this region was different than that in the remainder of the bay and did not allow the formation of a shallow aquitard. Based on the GPR transects from this region of the bay, we estimate that this atypical zone has a total area of 8.3 ha (Figure 7). The impact of this area on Juniper Bay's hydrology is not yet fully understood, but hydrologic measurements to date indicate that ground water inflow from adjacent upland is occurring in this area and affecting water-table levels within 3 m of the surface (Vepraskas et al. 2005).

Ditch-Induced Aquitard Discontinuities

Based on our manual measurements of ditch depths, the GIS map of Juniper Bay's topography was found to have an average absolute deviation of 23 cm for determining ditch depth (Figure 9). There was no apparent trend for the GIS map to either overestimate or underestimate ditch depth. The depths of aquitards interpreted from the GPR data were compared to the depths of adjacent ditches determined from the GIS map. This comparison could be made at the ends of the center and cross traces and along the entire edge traces, as the edge traces were adjacent to the edges of the lateral ditches (oriented approximately northwest to southeast; Figure 2). Depths to the aquitard surface along the edge traces and at the ends of the cross traces were compared to the depths of the lateral ditches. Depths to the aquitard surface at the ends of the edge and center traces were compared to those of the two main collector ditches (oriented approximately southwest to northeast) or the perimeter ditch, as appropriate. The GPR results did not indicate the thickness of the aquitards and, thus, only predicted where the tops of the aquitards were likely to have been pierced by ditches.

If the GPR estimates of aquitard depth and the ditch topography were perfectly known, then a ditch could be known to pierce the aquitard top if the ditch depth were greater than the aquitard depth. However, the aquitard depth and the ditch depth data had average

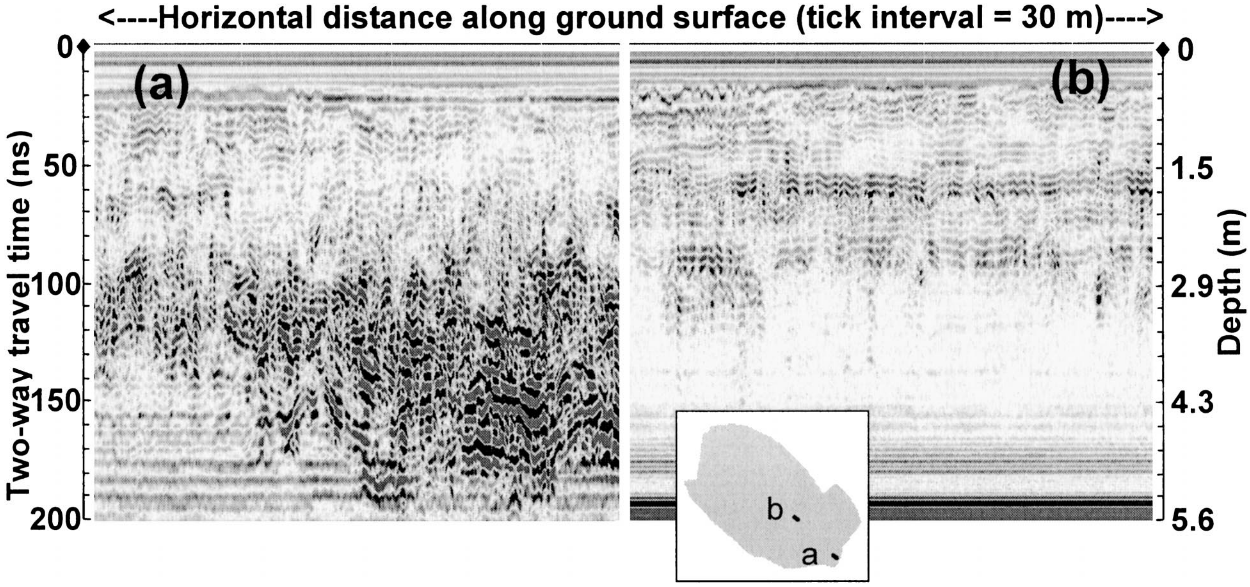

Figure 8. GPR profiles from Juniper Bay illustrating two contrasting radar facies. Profile (a) is from the atypical area in the southeast of Juniper Bay (inset map) that appears to be a fluvial deposit. The reflections are relatively high-amplitude, non-horizontal, chaotic, wavy, and discontinuous in the profile. Profile (b) is typical of the remainder of Juniper bay and appears to be lacustrine deposits. The higher amplitude (darker) reflections are nearly continuous, sub-parallel, and nearly horizontal. These higher amplitude reflections bound areas of the GPR profile that lack prominent reflections.

absolute deviations of 25 and 23 cm, respectively. To account for this uncertainty, a classification scheme was created that ranked the likelihood of a ditch having pierced the aquitard top. The classification scheme ranged from a very high to very low risk that a ditch pierced the aquitard top (Table 4).

The risk of ditches having pierced the aquitard top is low or very low throughout most of Juniper Bay (Figure 10). The main areas where lateral ditches pose a higher risk include Fieldlet 8; the southwest sides of Fieldlets 1, 4, and 5; the northeast sides of Fieldlets 2, 10, and 15; and the northwest ends of all of these fieldlets. Along the perimeter ditch, there is a greater risk of piercing primarily along the northwest boundary of the bay. The secondary collector ditch seems to pose little threat of piercing aquitard tops; however, the primary collector ditch shows a moderate to very high risk in numerous locations along its extent.

Coring data were used to supplement the risk assessment and determine whether a ditch is likely to have penetrated entirely through an aquitard. The depths of aquitards, as confirmed by coring, were compared to ditch depths within the areas of high risk. This investigation revealed that, in most instances, the aqui-

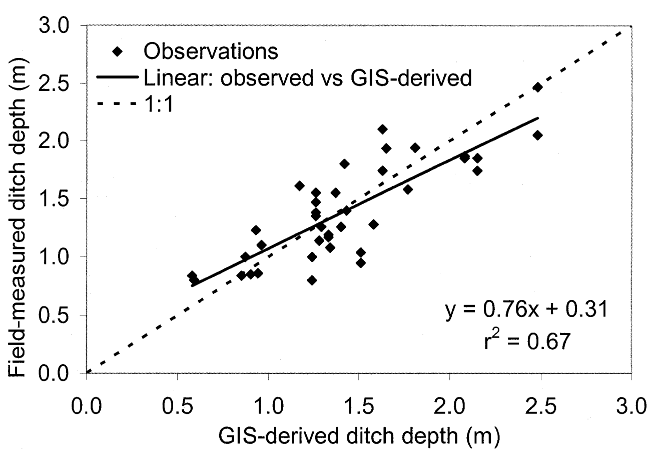

Figure 9. Field-measured versus GIS-derived ditch depths based on photogrammetry at 38 locations distributed throughout Juniper Bay.

Table 4. Classification scheme used to determine the risk that a drainage ditch has pierced the top of an aquitard. To determine the appropriate risk category for each point, ditch depths (DD) from the GIS topography map and aquitard depths (AD) from GPR interpretations were compared. The error value of 23 cm was used in the determination because this was the average absolute deviation in the DD measurement and approximated the average absolute deviation in the GPR interpretations (25 cm).

Risk of Ditch Having Pierced Top of Aquitard	Criteria
Very low	$23 \leq$ (AD–DD)
Low	0 cm $\leq$ (AD–DD) $<$ 23 cm
Moderate	-23 cm $\leq$ (AD–DD) $<$ 0 cm
High	$-46 \leq$ (AD–DD) < -23 cm
Very high	(AD–DD) < -46cm

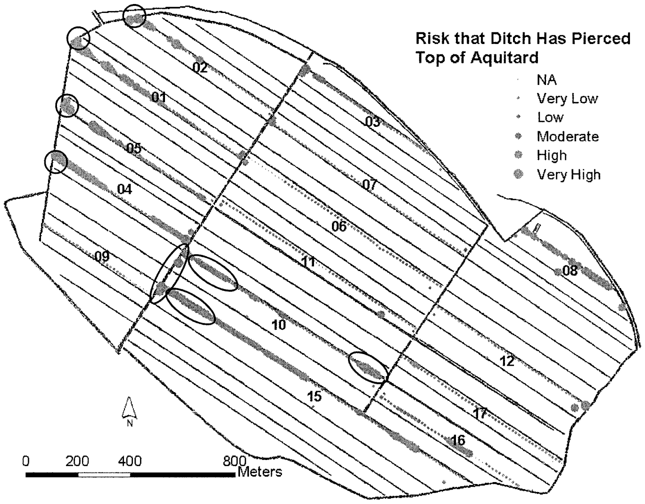

Figure 10. Map of Juniper Bay displaying the risk that a drainage ditch has pierced the top of an aquitard. Sizes of points are based upon the classification scheme presented in Table 4. Each point represents an observation point where the depth to a moderately fine- or fine-textured aquitard was determined via GPR interpretation. Identification numbers of fieldlets are shown as in Figure 2. Ditches within ovals and circles are suspected to have pierced entirely through aquitards based on ground truthing of GPR interpretations via coring records. If there are downward hydraulic gradients in these areas, they may ''leak'' and hinder restoration of wetland hydrology. Similar problems could occur in areas where shallow aquitards are absent as shown in Figure 7.

tards were thick enough that it is unlikely they have been entirely pierced by ditches. Exceptions to this are circled in Figure 10 and include the perimeter ditch around the northwest boundary of the bay, the northwest ends of Fieldlets 10 and 15, the southeast end of Fieldlet 10, and the southwest portion of the primary collector ditch. In the first three exceptions, ditching has probably pierced the shallowest aquitard (at about 1- to 1.5-m depth) but not the underlying aquitards (about 2- to 3-m depth). It is likely that the primary collector ditch has pierced all detected aquitards along its southwest extent, especially around Fieldlets 9, 10, and 15. Where aquitard piercing exists, hydraulic gradients and drainage of the bay are likely to be impacted. If the hydraulic gradient is downward, it may be necessary to install impervious liners in the affected ditches, or plug them with fill material having low hydraulic conductivity, in order to prevent leakage and allow restoration of wetland hydrology. Conversely, if there are upward hydraulic gradients where ditches have pierced aquitards, upward ground-water flow from a deeper saturated zone might actually enhance restoration of wetland hydrology.

Comparison of Cost and Time Requirements between GPR and Conventional Methods

The comparison of proposals submitted for GPR and conventional methodologies revealed a marked advantage for GPR in time and cost (Table 5). The proposed GPR survey would cost $20,488 and could be completed in 15 days. Depending on the spacing between coring sites, the proposals for the coring survey ranged in cost from $24,555 to $391,512 and in days from 16 to 257. The data in Table 5 include a calculation of the time and monetary savings provided by the GPR survey.

Others have shown the efficacy of GPR surveys as well. Collins and Doolittle (1987) used GPR to study soil microvariability and estimated that productivity in terms of information produced per unit labor time was increased by 800% compared to manual coring. Mokma and Doolittle (1993) made a direct comparison of soil maps achieved by GPR and by coring, and they found that GPR increased productivity by 133%. The only known report that included a quantitative estimate of financial benefits of GPR was that of Doolittle (1987). While using GPR to aid in soil mapping, he found that GPR decreased cost by 70% and increased productivity by 210%. When considering the efficiency and financial benefits of GPR, it is important to consider the resultant product along with benefits. Is GPR use justified if time and money savings are at the expense of a useable product? When Mokma and Doolittle (1993) reported their time savings with GPR use, they also reported that soil maps produced by coring and GPR were in 84% agreement. Although some

Table 5. Qualitative comparison of proposed GPR and coring surveys to determine depth of clayey aquitards along all ditches in Juniper Bay. Values are based on cost estimates by two anonymous consulting firms in response to requests for proposals. Productivity is defined here as information gathered per unit labor time.

Survey Type	Days to Complete	Cost ($)	Productivity Increase with GPR (%)	Cost Saving with GPR (%)
GPR	15	20,488	NA	NA
Coring at 15-m spacing	257	391,512	1613	1811
Coring at 60-m spacing	68	103,634	353	406
Coring at 300-m spacing	16	24,555	7	20

studies have found GPR to yield an unreliable result in some soils without expansive (and expensive) ground truthing (Doolittle et al. 2000), in many soils situations where the depth and continuity of a subsurface feature is of interest, GPR may indeed provide better results than coring (Collins et al. 1989, Mokma et al. 1990).

For the Juniper Bay comparison, the different core spacing scenarios were chosen intentionally to create a meaningful contrast between the resulting products. The 15-m core spacing matches the spacing of aquitard depth prediction points during the actual GPR survey at Juniper Bay. Thus, this variation in the coring proposal would provide the same density of depth information. The coring survey would provide more reliable data, as it does not involve potential interpretation error, but this reliability requires an extreme time and cost commitment. Even the coring scenario with 60-m spacing would probably be cost- and time-prohibitive. The coring variation with 300-m spacing was chosen because it could be achieved in approximately the same time as the GPR survey. However, the product of the 300-m coring survey provides a very low density of information compared to the other coring surveys or the GPR survey. Even though the time investment is comparable between the 300-m coring survey and the GPR survey, the cost of the coring survey is nearly 20% greater. Although this comparison of GPR and coring surveys was based on professional proposals and not actual work performed, it does indicate that GPR can provide a large volume of reliable data in a fraction of the time and cost required by conventional methods.

SUMMARY AND CONCLUSIONS

The GPR survey at Juniper Bay was successful in revealing the depth and extent of moderately fine- and fine-textured aquitards within a depth of ~5 m of the surface and in estimating where aquitard tops were penetrated by drainage ditches. Restoring wetland hydrology to fields drained by open ditches can be achieved by filling the ditches or by simply plugging their outlets. Ditch filling comes closest to returning the area to what it was before drainage, but this can be expensive. Plugging the drainage outlet is less expensive and can be achieved quickly. However, plugging may allow ditches to ‘‘leak’’ if the ditch penetrates through an aquitard into a sandy layer of high permeability and there is a downward hydraulic gradient. Our results estimated where surface ditches have penetrated the aquitard (Figure 10). If there are downward hydraulic gradients in these areas and/or in the area of the bay that has no shallow aquitards (Figure 7), ditch filling and/or lining may be needed there to ensure that wetland hydrology is restored. The necessary filling would be of relatively small extent. A cost-benefit analysis might be useful to help determine whether the cost of ditch filling and/or lining would be warranted relative to any additional mitigation credit that might be earned through restoring wetland hydrology to a greater area of the bay.

Based on proposals by professional firms, GPR was shown to provide a large volume of data in a time- and cost-effective manner. Given the positive results obtained in this study and the efficient characteristics of GPR surveys, we believe that our approach could be valuable in future wetland restoration projects in the Atlantic Coastal Plain and other regions with similar soils.

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